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Composite Waveform Generation for EMP and Lightning Direct-drive Testing

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1. Background

An integral portion of electromagnetic transient (EMT) testing is the survivability assessment. The ultimate goal of the survivability assessment is to establish the margin of survivability for the system under test. The margin of survivability is the ratio of system strength to anticipated stress. Within the EMP community, the anticipated stress reflects the responses induced by the simulated EMP environment and extrapolated to the Bell Laboratory's Generalized High-Altitude EMP Waveform; the system strength reflects the stress level required to upset or damage the system under test. One key approach to determine system strength is direct-drive testing. Direct-drive testing involves re-injecting amplified versions of the maximum response waveform at each test point until an operational upset occurs or an accepted drive level is attained. The maximum response waveforms are acquired by measuring defined test points for various simulated EMP environments with the system under test in various orientations and operational configurations.

Direct-drive testing presently uses only the measured waveform with the largest peak amplitude. As a result, much of the acquired data goes unused. Recently, the stress envelope technique was proposed to make more effective use of available data. This technique computes a composite waveform, referred to as the stress envelope, using all available data. Thereby, constructing a more conservative threat waveform, which incorporates more characteristics of the response waveforms and serves to more completely bound the response profile. Ultimately, this technique could be used to assess system and subsystem vulnerabilities to several EMT environments either singly or simultaneously, i.e., lightning, EMP, and electrostatic discharge. The stress envelope technique was initially described by one of the authors (Frazier) in 1992. An example of the stress envelope concept is given in figure 1.

This evaluation assessed two stress envelope techniques: (a) autoregressive (AR) technique and (b) Pulse and Damped Sine Characterization (PDSC). The AR technique was developed by the Naval Postgraduate School; the PDSC technique was developed by the Naval Air Warfare Center, Aircraft Division (NAWC-AD). Both techniques were developed in support of the Fleet Aircraft Assessment for Navy Testing and Analysis for EMP Limitation Program.

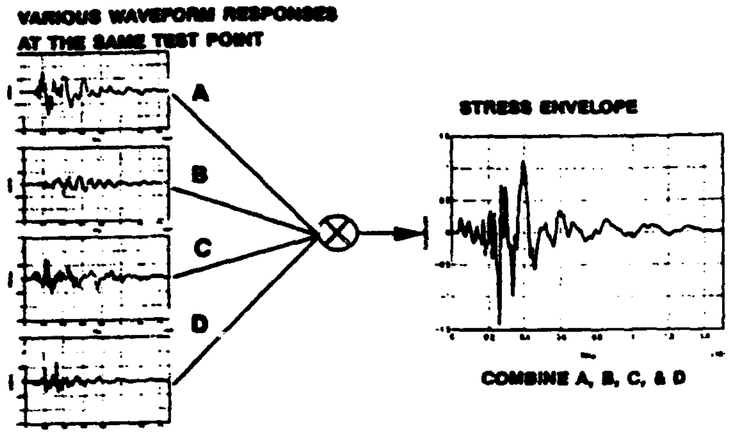

Figure 1. Stress Envelope Combination Technique

2. Technical Approach

2.1 Stress Envelope Derivation

Each technique was used to produce a set of stress envelopes from extrapolated test data. A total of 35 test points was selected; the selected test points were chosen if data were available for all experimental configurations. The aircraft was tested in each of the following four configurations: (a) fuselage parallel to the antenna in a horizontally-polarized electric field; (b) fuselage perpendicular to the antenna in a horizontally-polarized electric field; (c) fuselage nose-on to the antenna in a vertically-polarized electric field; and, (d) fuselage port wing-on to the antenna in a vertically-polarized electric field.

The AR technique used an Intel 486-based PC to construct stress envelopes. The AR technique employs a MATLAB-based algorithm, which is described by Tse in 1993. The PDSC technique used a DIGITAL MicroVAX II minicomputer to construct stress envelopes. The PDSC technique employs a FORTRAN-based algorithm. The resulting stress envelopes were evaluated on an Intel 486-based PC using the Aircraft Analysis, Modeling, and Prediction of E^3 Responses and Effects (AAMPERE) program. AAMPERE is a MATLAB-based package developed by the NAWC-AD for analysis of EMT data.

This evaluation was originally intended to evaluate three stress envelope techniques, as shown in figure 2: (a) AR, which uses a 12^{th}-order, all-pole, time-domain model for each data set; (b) PDSC, which uses the frequency-domain poles (both real and complex) for each data set; and, (c) autoregressive-moving average (ARMA), which uses an 11^{th}-order, pole/zero, time-domain model (six poles, five zeroes) for each data set. At the time of this evaluation, work had been completed on the former two techniques; the ARMA technique had not been completed.

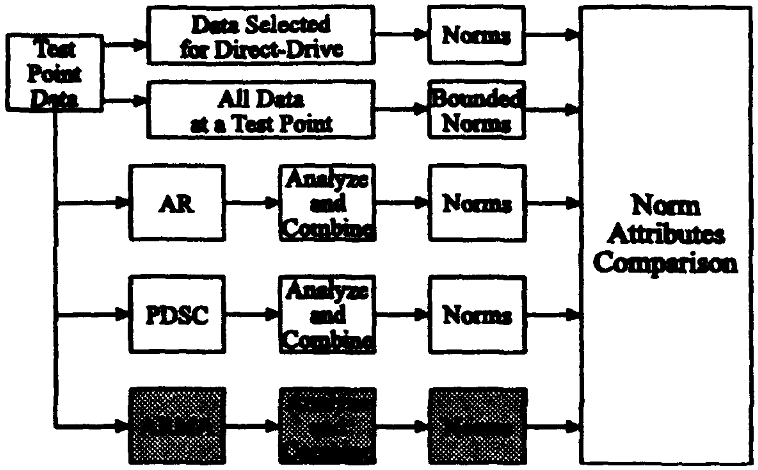

Figure 2. Waveform Norm Attribute Analysis

2.2 Analysis Approach

Each technique was evaluated using two approaches: (a) statistical comparison of stress envelopes to individual waveforms using waveform norm attributes (described by Baum in 1983) and (b) graphical comparison of stress envelopes to individual waveforms. The statistical analysis provided a quantitative comparison between stress envelopes and two predefined baselines (direct-drive baseline and bounded baseline). The graphical analysis provided a qualitative comparison between stress envelopes and constituent data.

Two important criteria for assessing the quality of the stress envelope techniques are: (a) obtaining a composite waveform, which provides an accurate, conservative bounding of the available data and (b) computing a composite waveform, which is not overly conservative and does not severely overstress the system. This evaluation used statistical analysis to address these criteria in assessing the available stress envelope techniques. The ultimate goal is to produce direct-drive waveforms, which represent conservative bounds of available data.

The statistical analysis compared the norm attributes of the stress envelopes to those of two predefined baselines. The direct-drive baseline was defined as the norm attributes of the waveforms currently selected for direct-drive testing. The current direct-drive waveforms reflect the data set with the maximum peak amplitude at a given test point. The bounded baseline was defined as the maximum norm attributes of all waveforms at a given test point. As a result, the bounded baseline is slightly more conservative, and is used as the primary point of comparison for this evaluation.

The graphical analysis compared the stress envelopes to the constituent data sets. The graphical comparison provided a qualitative visual review of the stress envelopes with respect to the original data sets. No statistical quantities were derived from this comparison.

A typical example of th ures used for the statistical analysis is shown in figure 3. Each of the figures includes the following elements: (a) a solid line indicating the appropriate baseline norm values; (b) a set of crosses indicating the stress envelope norm values; (c) a dotted line indicating the statistical mean above the appropriate baseline; and, (d) the statistics associated with the difference between the stress envelope and the appropriate baseline. The statistics are expressed in decibels (dB) and are computed according to equation (1):

$$R = 20 * \log_{10}\left(\frac{N_{Envelope}}{N_{Baseline}}\right) \tag{1}$$

2.3 Waveform Norm Attributes

The statistical comparison of stress envelopes to individual waveforms is based upon waveform norm attributes. Waveform norm attributes, commonly referred to as norm attributes, are thoroughly described by Baum, Knupp, and McLemore. Briefly, the work performed in 1983 by Carl Baum defined several important time-domain scalar quantities associated with each waveform. This work was then expanded upon by Knupp and McLemore in 1988.

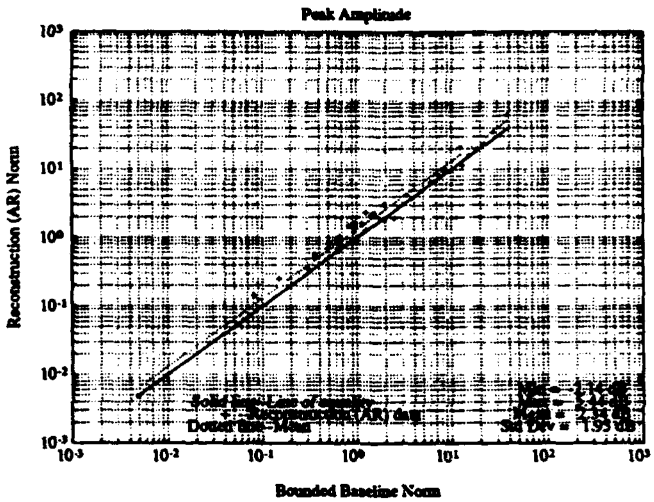

Figure 3. Typical Comparison Result

Five of these quantities, which are accepted throughout the EMP community, were used to analyze the available stress envelope techniques: (a) peak amplitude, N_1, which reflects the maximum signal amplitude; (b) peak derivative, N_2, which reflects the maximum signal derivative, i.e., maximum rate-of-rise; (c) peak impulse, N_3, which reflects the maximum signal time-integral; (d) rectified impulse, N_4, which reflects the total charge passing the measurement point; and, (e) root action integral, N_5, which reflects the total energy passing the measurement point. Table I provides a summary of these quantities and the appropriate equations.

Each of these quantities are considered to provide important statistical insights into the survivability of the system. The first and last quantities, peak amplitude and root action integral, are to be most significant in this report because they are most closely associated with circuit upset and component failure, respectively.

Table I. Waveform Norm Attributes

Norm	Equation	Nomenclature
N_1	$\mid f(t) \mid_{max}$	Peak Amplitude
N_2	$\left\| \frac{df(t)}{dt} \right\|_{max}$	Peak Derivative
N_3	$\left\| \int_0^t f(x)\, dx \right\|_{max}$	Peak Impulse
N_4	$\int_0^\infty \|f(t)\|\, dt$	Rectified Impulse
N_5	$\int_0^\infty \|f(t)\|^2\, dt$	Root Action Integral

3. Statistical Comparison of Bounded Baseline to Direct-Drive Baseline

As noted earlier, the bounded baseline is considered to be slightly more conservative, and was selected as the primary standard for evaluation purposes. This selection was made after performing an initial analysis, which compared the bounded baseline to the direct-drive baseline. The analysis was performed to address two considerations: (a) is the premise that the bounded baseline reflects greater conservativism accurate and (b) how conservative is the bounded baseline with respect to the direct-drive baseline?

The bounded baseline reflects the set of maximum norm attributes for a given test point. For example, four waveforms--X_A, X_B, X_C, and X_D--were acquired at test point X. Assume that waveform X_A had the largest peak amplitude and peak impulse; waveform X_B had the largest peak derivative and rectified impulse; and, waveform X_D had the largest root action integral. For test point X, the bounded baseline would include norm attributes from waveforms X_A, X_B, and X_D. In comparison, the direct-drive baseline reflects norm attributes exclusively from the waveform, which would be selected for direct-drive testing using the present approach, (i.e., waveform X_A since it had the largest peak amplitude). For a majority of the cases, the maximum norm attributes are associated with the waveform having the largest peak amplitude. In general, however, this case is not always true. The bounded baseline tends to reflect a more conservative estimate. As a result, the bounded baseline was selected as the primary standard for evaluation purposes.

The analysis used the same general approach as that described for the comparison between stress envelopes and appropriate baselines. The statistics (given in table II) are expressed in dB and are computed according to equation (2):

$$R = 20 * \log_{10}\left(\frac{N_{Bounded\ Baseline}}{N_{Direct-Drive\ Baseline}}\right) \quad (2)$$

The statistics in table II seem to support the premise that the bounded baseline is more conservative than the direct-drive baseline. The minimum difference between the two baselines is 0 dB, which indicates that all bounded baseline norm attributes fall on or above the line defined by the direct-drive baseline. In addition, the conservativism inherent in the bounded baseline is not substantial. The means of the distribution are never greater than 4 dB and is less than 1 dB for all norm attributes except peak impulse. This result indicates that the bounded baseline approach yields slightly more conservative results. Hence, fair confidence for the decision to use the bounded baseline for evaluation purposes.

Table II. Statistical Comparison of Bounded Baseline to Direct-drive Baseline

Norm Attribute	Min. (dB)	Max. (dB)	Mean (dB)	Std. Dev. (dB)
Peak Amplitude	0	0	0	0
Peak Derivative	0	5.12	0.59	1.36
Peak Impulse	0	16.64	3.81	5.20
Rectified Impulse	0	5.23	0.56	1.18
Root Action Integral	0	1.85	0.20	0.52

4. Statistical Comparison of Stress Envelopes to Bounded Baseline

A primary analysis was performed, which compared the norm attributes for the stress envelopes to the bounded baseline. This comparison was done to assess the available stress envelopes with respect to a bounding across all waveforms. Again, the bounded baseline reflects the set of maximum norm attributes for a given test point, which tends to reflect a more conservative estimate and was selected as the primary standard for evaluation purposes. The statistics associated with the bounded baseline comparison are given in table III.

Analysis of four of the five norm attributes (peak amplitude, peak derivative, rectified impulse, and root action integral) indicates both stress envelope techniques produce estimates, which have approximately the same mean. However, three of the five norm attributes (peak amplitude, peak derivative, and root action integral) yielded PDSC distribution standard deviations two to three times greater than those for corresponding AR distributions. Graphical comparisons to the bounded baseline shows that the PDSC technique produces a more variable result. With regard to these analyses, the AR technique is statistically more stable. In fact,

Table III. Statistical Comparison of Stress Envelopes to Bounded Baseline

	AR Stress Envelope				PDSC Stress Envelope			
Norm Attribute	Min. (dB)	Max. (dB)	Mean (dB)	Std. Dev. (dB)	Min. (dB)	Max. (dB)	Mean (dB)	Std. Dev. (dB)
Peak Amplitude	-2.14	5.44	2.34	1.95	-10.74	23.44	2.28	6.77
Peak Derivative	-9.54	6.86	1.18	3.47	-26.65	25.94	0.73	11.18
Peak Impulse	-14.01	7.91	-2.83	4.45	-37.32	7.30	-8.20	9.56
Rectified Impulse	-13.94	4.94	-0.58	3.28	-2.67	9.22	2.94	3.27
Root Action Integral	-4.26	5.34	1.71	1.66	-3.97	16.59	3.01	4.36

use of the PDSC waveforms during a direct-drive test could overstress the systems under evaluation. This is especially critical for peak amplitude and root action integral.

Analysis of peak impulse provides somewhat different results. Unlike the previous quantities, the PDSC results do not compare favorably with equivalent AR results. For peak impulse, the PDSC consistently produces an envelope, which substantially undershoots the bounded baseline. Previously, the two techniques performed comparably with the AR technique producing a tighter distribution. Graphical comparison to the bounded baseline shows that the PDSC technique produces variable results, which is supported by the statistics. With regard to the peak impulse analysis, the AR technique is statistically more stable. In fact, use of the PDSC waveforms during a direct-drive test would not provide a stress comparable to the present direct-drive test approach (at least, with regard to peak impulse).

5. Statistical Comparison of Stress Envelopes to Direct-drive Baseline

A second analysis was performed, which compared the norm attributes for the stress envelopes to the direct-drive baseline. This second comparison was done to assess the available stress envelopes with respect to direct-drive waveforms as presently selected. Again, the direct-drive baseline reflects the norm attributes from waveforms currently selected for direct-drive testing. The statistics associated with the direct-drive baseline comparison are given in table IV.

The results proved to be very similar in this comparison (in fact, they are equivalent for the peak amplitude comparison). As a consequence, the conclusions drawn in the previous section are also true with regard to statistical stability and preferred stress envelope usage.

Table IV. Statistical Comparison of Stress Envelopes to Direct-drive Baseline

	AR Stress Envelope				PDSC Stress Envelope			
Norm Attribute	Min. (dB)	Max. (dB)	Mean (dB)	Std. Dev. (dB)	Min. (dB)	Max. (dB)	Mean (dB)	Std. Dev. (dB)
Peak Amplitude	-2.14	5.44	2.34	1.95	-10.74	23.44	2.28	6.77
Peak Derivative	-9.54	8.63	1.77	3.89	-26.65	25.94	1.33	11.28
Peak Impulse	-14.01	15.62	0.99	7.36	-37.32	11.35	-4.39	10.41
Rectified Impulse	-13.94	6.30	-0.01	3.63	-1.96	12.06	3.50	3.33
Root Action Integral	-4.26	6.69	1.91	1.84	-3.97	16.59	3.21	4.44

6. Graphical Comparison Between Stress Envelope Techniques

As noted earlier, the stress envelope technique was developed to produce a more conservative waveform for direct-drive testing. The resulting composite waveform bounds the response profile and incorporates more characteristics of all response waveforms. The statistical analysis indicated the stress envelope technique was addressing both conditions. In addition, the statistical analysis indicated the AR technique was providing a more robust result. However, these results were based solely upon statistical considerations. While two stress envelopes may be statistically equivalent, either may be considered unacceptable to an analyst.

To further assess the quality of the reconstructions, a graphical comparison was performed. This comparison was a qualitative comparison between the two stress envelope techniques. A set of ten test cases were chosen to support this comparison. Two norm attributes were used as screens: (a) peak amplitude and (b) root action integral. The test cases reflected the largest differences between the AR technique and the PDSC technique. Presumably, the data sets with the greatest disparities should reflect the most obvious differences in processing quality. The ratios, as expressed in dB, are computed according to equation (3):

$$R = 20 * \log_{10} \left(\frac{N_{AR}}{N_{PDSC}}\right) \tag{3}$$

Each of the test cases was compared to the response waveforms. An attempt was made to assess the acceptability of each stress envelope. In each case, a dominant waveform was identifiable (with respect to norm attributes) and characteristics of that waveform were anticipated in the stress envelope.

The reader is reminded again, the results given in the following discussion reflect general classes of results drawn from a small subset of available data. The bulk of the analysis is based upon 35 test points, which is approximately 10% of the total number of test points. As a result, the percentages noted previously reflect an examination of approximately 3% of available data, and should be reviewed accordingly.

Review of the test cases indicated that both techniques produced waveforms of acceptable quality in most cases (approximately 60%). However, for the remainder of the test cases, each of the techniques would perform preferentially. That is to say, for approximately 20% of the test cases, the AR technique outperformed the PDSC technique; for the remaining 20% of the test cases, the PDSC technique outperformed the AR technique. Presumably, the stress envelopes are data-dependent or data-sensitive, and further research should be conducted to isolate any numerical irregularities.

In approximately 60% of the test cases, both techniques performed adequately. For this comparison, a stress envelope is considered to be adequate if it appears to be a reasonable construction based upon the initial data waveforms. This assessment reflects an analyst's qualitative appraisal.

For the case of balanced performance, either of these reconstructions would be acceptable as a direct-drive waveform. The PDSC stress envelope appeared to favor one waveform more strongly but its magnitude was almost twice that of the waveform (which was the largest). The AR stress envelope tended to favor a different waveform but its magnitude was slightly lower than either of the two waveforms.

In approximately 20% of the test cases, the AR technique performed somewhat better, and would be preferable as a direct-drive waveform. The AR stress envelope appeared to incorporate more of the composite characteristics of the data waveforms, and had a more reasonable magnitude (if slightly lower than the maximum). The PDSC stress envelope tended to favor a single waveform most but its magnitude was almost 60% greater than the waveform (which was the largest). Again, the stress envelope is supposed to produce an accurate, conservative, bounding waveform, which is not too conservative and does not overstress the system. For this case, the AR stress envelope more adequately addressed the criteria.

For the remaining 20% of the test cases, the PDSC technique performed somewhat better, and would be preferable as a direct-drive waveform. The PDSC stress envelope appeared to incorporate more of the composite characteristics of the data waveforms, and had a more reasonable magnitude. The AR stress envelope did not appear to provide an adequate model of the available data. Again, the stress envelope is supposed to produce an accurate, conservative, bounding waveform, which is not too conservative and does not overstress the system. For this case, the PDSC stress envelope more adequately addressed the criteria.

7. Conclusions and Recommendations

In the bounded baseline comparison, the AR technique appeared to provide statistically more stable results than the PDSC technique. Both techniques produced comparable means for four of the five norm attributes (peak amplitude, peak derivative, rectified impulse, and root action integral.) However, the standard deviation of the PDSC distribution was two to three times greater than that of the AR distribution.

This variability is a concern when considering the potential for overstressing or understressing systems. With regard to peak amplitude, peak derivative, and root action integral, use of the PDSC waveforms during a direct-drive test could substantially overstress the systems under evaluation. This is especially critical for peak amplitude and root action integral, and should be avoided.

With regard to the peak impulse, the PDSC consistently produces an envelope, which substantially undershoots the bounded baseline. In fact, use of the PDSC waveforms during a direct-drive test would not provide sufficient stress to evaluate the systems under evaluation. While this runs counter to the other statistics, it still supports the inclination to use the AR stress envelope technique.

The results of the direct-drive baseline analysis are consistent with the bounded baseline analysis. As a result, comparison between AR and PDSC lead to the same conclusions: (a) the AR technique appeared to provide statistically more stable results than the PDSC technique and (b) use of the PDSC waveforms during a direct-drive test could substantially overstress the systems under evaluation.

Graphical analysis of a small set of test cases indicated that both techniques produced waveforms of acceptable quality in most cases (approximately 60%). However, for the remainder of the test cases, each of the techniques would perform preferentially. For approximately 20% of the test cases, the AR technique outperformed the PDSC technique; for the remaining 20% of the test cases, the PDSC technique outperformed the AR technique. Presumably, the stress envelopes are data-dependent or data-sensitive, and further research should be conducted to isolate any numerical irregularities.

Since both techniques produce acceptable results, a composite approach is recommended, which makes use of both techniques as appropriate. The AR technique should be used to compute the preliminary set of stress envelopes. The AR stress envelopes should be reviewed to ensure that they are acceptable for direct-drive testing. Any stress envelopes, which are found to be unacceptable, should be processed using the PDSC technique. The PDSC stress envelopes should be reviewed to ensure that they are acceptable for direct-drive testing. This second review is crucial since PDSC tends to produce stress envelopes, which may overstress the systems under evaluation. Any PDSC stress envelopes, which are deemed acceptable but too strenuous should be rescaled to an acceptable level. A reasonable level would be 3 dB above the largest peak amplitude. Any test points, which yield unacceptable results using both stress envelope techniques, should use the direct-drive test approach used at present, i.e., use the waveform with the maximum peak amplitude.